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Indigo Dyeing of *Cyperus rotundus* Fibers: A Sustainable Approach to Developing Environmentally Friendly Materials

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Abstract

Natural indigo dyeing has re-emerged as a sustainable alternative to synthetic dyes, driven by increasing global demand for eco-friendly materials and the need to reduce chemical dependence in textile and craft production. In response to these sustainability challenges, this study aimed to apply natural indigo dyeing techniques to *Cyperus rotundus* fibers as an innovative material process and to design community-based products derived from *C. rotundus* within the framework of the green economy. The results showed that the color shades of *C. rotundus* and *C. mitis* fibers varied depending on the mordanting conditions. Dyeing experiments were conducted using three formulations, and color characteristics were evaluated using the CIELAB system to assess hue variation and color depth. Mechanical properties were further examined through tensile testing to determine material performance. Fibers pre-soaked in clay solution produced dark blue to indigo-green hues with good color fastness, though with some uneven color distribution ($a^* = -9.63$; $b^* = 3.21$). Fibers dyed with indigo mixed with vinegar exhibited dark green to yellowish hues, also displaying uneven coloration ($a^* = -6.88$; $b^* = 1.28$). The moisture content of dyed *C. rotundus* fibers averaged 11.55%, while tensile strength measurements recorded maximum forces of 112.15 N, 44.54 N, and 62.78 N (average 73.16 N). These findings confirm the feasibility of converting dyed *C. rotundus* fibers into sustainable, environmentally friendly materials suitable for community-level product innovation. Overall, the study highlights the potential of utilizing *C. rotundus*, an invasive weed, as an alternative natural fiber source for eco-friendly and culturally rooted community products that support sustainable livelihoods and contribute to the creative economy.

Keywords

Indigo dyeing; Cyperus rotundus; Eco-friendly products; Natural fibers; Sustainable innovation

Introduction

Thailand's 20-Year National Strategic Plan (2018–2037) aims to guide the country's long-term development through innovation, inclusivity, and sustainability. Within this framework, the strategy highlights the importance of strengthening grassroots economic systems, particularly through skill development and the application of cultural capital to enhance local products. The ultimate goal is to increase community income generation by fostering creativity and innovation under the concept of the "creative economy." A key policy direction has been the promotion and development of the agro-processing industry to produce high-value products, thereby upgrading product standards. At the same time, state policy emphasizes the conservation, revitalization, and dissemination of cultural heritage and local wisdom, as well as empowering communities to achieve sustainable self-management.

Thailand's cultural diversity, rooted in its many ethnic groups, provides a strong foundation for the creative economy and tourism sectors. Nevertheless, cultural products, particularly those produced by local communities or community enterprises, have often failed to gain significant recognition in broader markets. The challenges include the lack of product innovation, insufficient differentiation, and limited responsiveness to modern consumer demand. Many cultural products lack distinct identities, while local industries face labor shortages and insufficient technical expertise to sustain quality and production growth that would help them stand out in highly competitive markets.

To address these challenges, the Department of International Trade Promotion (DITP) has introduced lifestyle product development initiatives as part of the "market-led production" strategy under the Ministry of Commerce's accelerated export promotion program. These initiatives aim to enhance product value through the adoption of the Bio-Circular-Green (BCG) Economy Model, targeting new consumer groups with strong purchasing power and positioning Thailand as a regional hub for lifestyle and design-oriented fashion products. Currently, Thai lifestyle and fashion products are internationally recognized for their quality, craftsmanship, diversity of raw materials, and integration of Thai cultural identity into design. In 2024, exports of lifestyle and fashion products were projected to exceed 323 billion baht. Significantly, the lifestyle and fashion industry also plays a vital role in national economic development, as over 90% of its enterprises are small and medium-sized enterprises (SMEs), creating more than two million jobs across supply chains (BangkokBizNews, 2024). Scholars have emphasized that the transition toward circular and green economy frameworks is essential for strengthening community-level production and reducing environmental impacts (Toponar *et al*., 2024). Evidence from community-based resource management also shows that eco-friendly production enhances local livelihoods and supports resilient value chains (Shrestha, Shrestha and Shah, 2020).

Equally important is the role of innovation in enhancing product competitiveness. Innovation has become a key driver of growth and national competitiveness in the digital economy and society. The World Intellectual Property Organization (WIPO) ranks countries based on innovation output. In 2019, Thailand was ranked 43rd globally, with notable performance in

the domains of institutions, human capital and research, business sophistication, and knowledge and technology outputs (National Innovation Agency, 2019).

Natural dyed products have gained increasing popularity, particularly in international markets (Department of Sericulture, 2023). This growing demand emphasizes environmentally friendly production processes and the distinctive qualities of natural dyes, which provide soft and subtle tones rather than bright or artificial hues. A significant advantage of natural dyes lies in their safety for human health when compared to synthetic dyes, which may cause skin allergies, irritation, or respiratory problems (Olas *et al*., 2024) . Furthermore, some synthetic dyes, such as azo dyes, can degrade into aromatic amines, compounds with carcinogenic properties (Weisburger, 2002). Recent studies highlight the growing relevance of natural indigo in sustainable textile production, particularly within eco-printing, color fastness enhancement, and product design applications (Mongkholrattanasit *et al*., 2022). Broader reviews of natural dyes confirm ongoing global research efforts to improve dye yield, reproducibility, and environmental performance (Pizzicato *et al*., 2023; Saxena and Raja, 2014).

Despite these advantages, natural dyes are limited by challenges such as low color yield, inconsistency in shades across dyeing batches, and difficulties in reproduction. Colors obtained from natural dyeing often fade or bleed during use, and their wash and light fastness are generally lower than those of synthetic dyes, making them less responsive to consumer expectations (Masae, Pitsuwan and Kongsong, 2024). To address these constraints, mordants such as lye water, banana sap, and clay have been introduced into natural dyeing processes to improve fastness and enhance fiber adherence (Kaenchan and Khamphiraphanphan, 2014).

According to Khieokaew and Reemsri, indigo dyeing represents an innovative approach that can be adapted to various types of products (Reemsri and Khieokaew, 2019). However, the chemical composition of natural indigo must be carefully modified to align with the characteristics of the fibers being dyed. The development of bio-based fibers and natural materials has also become a central focus of sustainable design research, with several studies reporting promising advances in fiber modification, durability, and eco-product applications (Torabizadeh *et al.,* 2020). Indigo-dyed products hold the potential to raise the production standards of local enterprises, enabling them to meet quality assurance requirements, including certifications such as the Green Products Certificate.

Historically, indigo has played a pivotal role in global trade, particularly along the Silk Road, where it was a key commodity exchanged through caravan routes. Indigo dyeing traditions are found in nearly every ASEAN country, as well as across Asia and Europe. Research shows that Japan is a major importer of indigo-dyed textiles, particularly from producers in Sakon Nakhon Province, Thailand. At present, indigo fabric production is widespread in ASEAN countries, with Cambodia and Laos actively promoting the preservation of indigo dyeing as a cultural art form. If Thailand can extend indigo-dyeing innovations to other types of products, it may open opportunities for greater regional and international collaboration (Reemsri and Khieokaew, 2019).

The functional performance of indigo-dyed textiles produced by community enterprises has also been confirmed in recent studies. Chollakup *et al.* (2023) investigated woven

cotton fabrics dyed with natural indigo and finished for home textile applications and reported that tensile strength, tear strength, pilling resistance, and colour fastness to washing, water, and light met ISO requirements for bed linens and pillowcases exported to the European Union, with only wet rubbing fastness remaining a limitation (Chollakup *et al*., 2023). Their work indicates that community-based production systems, when coupled with appropriate finishing techniques, can achieve export-level quality standards. Building on this evidence, the present study extends the scope of natural indigo applications from cotton fabrics to Cyperus rotundus fibers, aiming to develop eco-friendly materials suitable for community product innovation under the green economy framework.

In recent years, many countries have recognized the growing challenges posed by environmental change and have adopted the principles of the Bioeconomy, Circular Economy, and Green Economy (BCG model) to address pressing issues in agriculture, food production, natural resources, and environmental management. These frameworks have been applied to design and develop eco-friendly products, often referred to as Eco Design. The concept of Eco Design, promoted by business councils for sustainable development and widely endorsed by governments in several developed countries, has become an important driver of sustainable consumption and production (Aphirakthanakorn, 2017).

Global consumer behavior trends indicate that environmental consciousness is on the rise, particularly among younger generations. Over the past year, the number of consumers who seriously consider environmental impact when making purchasing decisions has grown significantly and is projected to continue increasing. Generation Z, in particular, has demonstrated heightened awareness of environmental issues, integrating eco-friendly choices into their daily lifestyles. Research in Thailand, conducted by Mahidol University's College of Management (CMMU), highlights the "Voice of Green" marketing survey conducted by the College of Management, Mahidol University (CMMU) examined 1,252 Thai consumers and reported that 74% of respondents were likely to adopt eco-friendly products and shift toward more sustainable lifestyles. In addition, 37.6% were classified as "true green" consumers who actively seek environmentally friendly products and are willing to pay premium prices for sustainable goods and services (Tharinphirom, 2020).

Sectors with the strongest potential for growth include: (1) products made from biodegradable and reusable materials, (2) businesses providing clean energy services, such as electric vehicle charging stations, (3) eco-friendly goods and services such as bio-based packaging and plant-based food alternatives, and (4) eco-products with innovative designs that resonate with the preferences of younger generations (Bangkok Bank, 2022). These findings underscore both the growing opportunities and the urgent need for industries to align product innovation with sustainable development principles in order to enhance competitiveness in the global market. Evidence from community sustainability research indicates that eco-friendly materials and resource-based local production contribute significantly to long-term socio-economic resilience (Hohol and Nedilska, 2021).

Despite strong policy and market frameworks, there remains a significant research gap concerning the scientific understanding of natural indigo dyeing on alternative plant fibers such as Cyperus rotundus. Previous studies have primarily focused on cotton, silk, or hemp, leaving limited data on how indigo pigments interact with the structural and chemical composition of Cyperus fibers. Questions remain regarding dye absorption mechanisms, color fastness, and the environmental performance of these fibers after dyeing. Addressing these gaps is essential to advancing sustainable material innovation that bridges traditional dyeing wisdom with modern eco-design technologies. This study, therefore, explores an experimental indigo dyeing process formulated specifically for Cyperus fibers to enhance color durability, ecological safety, and material value within Thailand's creative economy framework.

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Building upon the aforementioned problems and significance, this article forms part of a broader research initiative focusing on the development of eco-friendly community products derived from *Cyperus rotundus* fibers through natural indigo–dyeing innovations within the green economy paradigm. This overarching program provides the conceptual foundation for the present study, which aims to strengthen climate-resilient local production systems by transforming *C. rotundus* — a weed commonly associated with agricultural loss — into high-value, environmentally sustainable materials. As a naturally abundant resource, *C. rotundus* fibers offer clear ecological advantages, including biodegradability and the absence of long-term environmental impacts. Throughout the material development and product life cycle, this research emphasizes sustainability by reducing chemical-based weed control, minimizing open-field burning, decreasing plastic consumption, and eliminating synthetic dye usage. Importantly, the resulting products are biodegradable, ensuring minimal environmental burden at the end-of-life stage. The utilization of *C. rotundus* as an alternative natural material for eco-product innovation not only supports climate adaptation strategies but also aligns with the principles of the green economy, contributing to long-term community income generation and environmentally responsible production.

The specific research objectives are as follows:

1. To apply natural indigo dyeing techniques to *C. rotundus* fibers as an innovative material process.
2. To design community-based products derived from *C. rotundus* within the green economy framework.

Methodology

Research Design

This study adopted an experimental research design to investigate the dyeing characteristics of *Cyperus rotundus* fibers using natural indigo. The research focused on assessing fiber properties after dyeing, evaluating color variations under different mordanting conditions, and exploring the material's suitability for eco-friendly product development**.** Figure 1 illustrates the color variations observed in *Cyperus rotundus* and *Cyperus mitis* fibers dyed with natural indigo using different dye formulations.

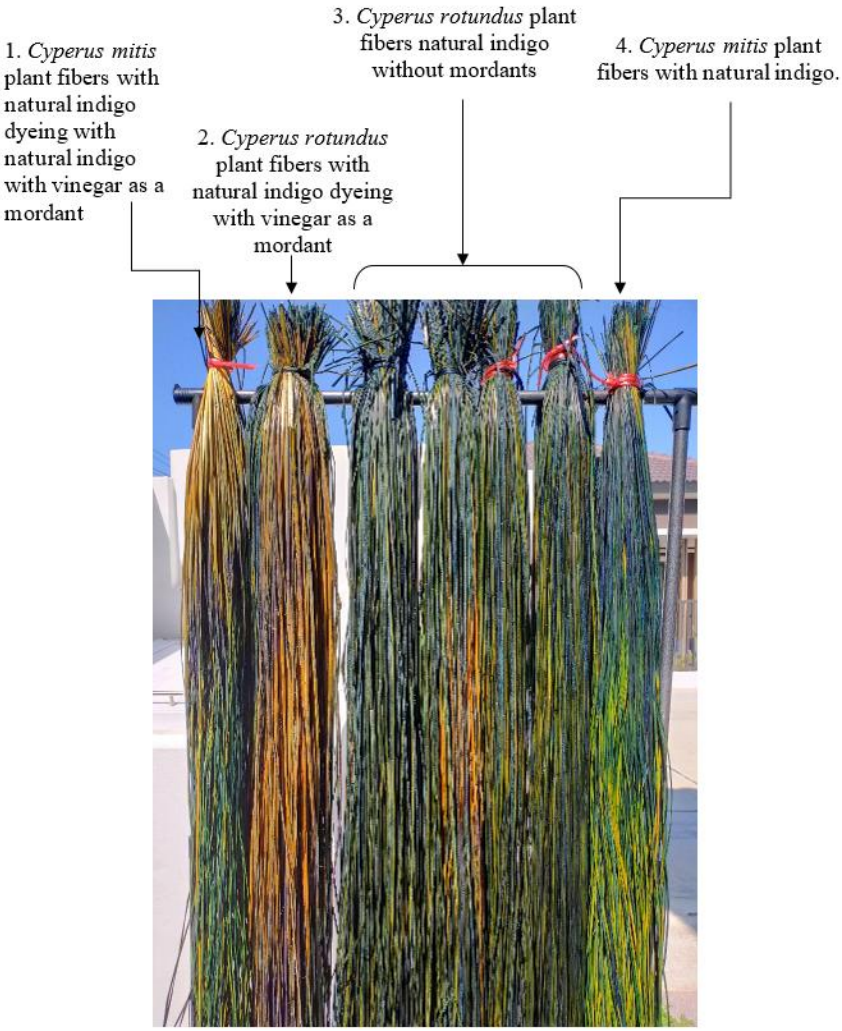
1. *Cyperus mitis* plant fibers with natural indigo dyeing with natural indigo with vinegar as a mordant
2. *Cyperus rotundus* plant fibers with natural indigo dyeing with vinegar as a mordant
3. *Cyperus rotundus* plant fibers natural indigo without mordants
4. *Cyperus mitis* plant fibers with natural indigo.

Figure 1: Coloration of *Cyperus rotundus* and *Cyperus mitis* fibers dyed with natural indigo using different formulations (*Source:* Chotinonphicha, 2025)

Plant Material Description

According to the Plant Protection Research and Development Office, Department of Agriculture (2022), *Cyperus rotundus* L. (commonly known as purple nutsedge) belongs to the family Cyperaceae and is one of the world's most invasive weed species. It is widely distributed across Thailand — from lowland rice paddies to upland areas — and exhibits strong adaptability to both moist and dry conditions. The species reproduces primarily through rhizomes and underground tubers, making eradication extremely difficult.

A closely related species, *Cyperus mitis* Steud. shares similar characteristics but can be distinguished by its taller stature and longer bracts that exceed the inflorescence length. Both species were selected for comparative purposes in this experiment due to their structural similarities and abundance in agricultural fields.

Description of Plant

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Fresh *C. rotundus* plants with stem diameters of approximately 0.5–1 cm and heights between 100–150 cm were harvested from paddy field areas. Stems were cleaned and cut longitudinally into thin strips using a sharp knife, producing 2–3 fibers per stem. The fibers were then sun-dried for 2–3 days to ensure complete dryness, which enhances their capacity to absorb natural indigo dye. To maintain consistency in subsequent testing, only mature stems with uniform appearance and without visible defects were selected. This selection procedure minimized variability in fiber quality before the dyeing process.

Experimental Procedure

The experiment utilized fresh indigo paste, *Cyperus rotundus* plant fibers, tap water, Thiourea dioxide (reducing agent), salt, vinegar, Dan Kwian clay, a colorimeter, and a Universal Testing Machine (UTM, Model NRI-TS500-20B). The experimental dyeing procedure followed the natural indigo method adapted from Chotinonphicha (2025), involving specific raw materials, mixtures, and process steps. According to Chotinonphicha (2025), the natural indigo dyeing of local plant fibers involves specific raw materials, mixtures, and procedures, as follows:

a) Preparation of Cyperus rotundus fibers: Fresh *C. rotundus* plants with diameters of approximately 0.5–1 cm and heights of 100–150 cm were cut longitudinally into thin strips using a sharp knife, producing 2–3 fibers per stem. The fibers were then sun-dried for 2–3 days to ensure complete dryness, which enhances their capacity to absorb natural indigo dye.

b) Dye bath formulation: The ingredients were prepared with defined proportions: Fresh indigo paste (1 kg), tap water (10 L, at ambient temperature), salt (10 g), Thiourea dioxide (600 g), and dried *C. rotundus* fibers (1 kg)

c) Preparation of the indigo dye solution: Ten liters of tap water at room temperature were poured into a plastic basin to serve as the dye bath. Thiourea dioxide (600 g) was added to the basin and dissolved thoroughly. Salt (10 g) was added and stirred until fully dissolved. Indigo paste (1 kg) was added, crushed, and kneaded until it dispersed completely into the solution. The mixture was stirred until foaming occurred. After 30–40 minutes, the foam changed from blue to yellow, and the solution developed into a reduced indigo dye bath.

d) Dyeing of C. rotundus fibers: One kilogram of dried *C. rotundus* fibers was immersed in the prepared dye bath. To ensure complete submersion, a weighted object was placed on top of the fibers. The fibers were soaked in the indigo solution for 24 hours. After soaking, the fibers were thoroughly rinsed with clean water and sun-dried until fully dry. The indigo-dyed fibers were then used for weaving mats on traditional looms, specifically as weft threads in horizontal weaving structures (Chotinonphicha, 2025).

Comparative Dyeing Experiments

Two experimental variations were tested to compare the effects of different mordants on dyeing outcomes:

1. Clay mordanting: Fibers pre-soaked in Dan Kwian clay solution before dyeing.
2. Vinegar mordanting: Vinegar is added directly into the dye bath.

Color variation and fastness were evaluated using the CIELAB color system. The influence of mordanting on hue shifts (a and b values) was analyzed following the methods described by Dunkhuntod *et al*. (2024). The mechanical strength of dyed fibers was assessed through tensile testing to determine suitability for use in product design (Dunkhuntod *et al*., 2024).

Standardization of Fiber Samples

Before laboratory testing, fiber samples were standardized to reduce experimental variability. Dyed *C. rotundus* fibers were cut to a uniform length of 25 cm, and test specimens were prepared with a dry weight of 1.5 ± 0.1 g per sample. Fiber width was controlled by using strips derived from identical longitudinal slicing of stems. All samples were conditioned at 28 ± 2 °C and approximately 65% relative humidity for 24 hours before measurement to stabilize moisture content and ensure comparable testing conditions.

Colorimetric and Mechanical Measurements

Colorimetric evaluation of dyed fibers was performed using the CIELAB color system. For each dyeing formulation, L* (lightness), a* (red–green coordinate), and b* (yellow–blue coordinate) values were recorded from triplicate measurements on representative fiber bundles. Lower L* values indicated darker shades, negative a* values indicated greener tones, and negative b* values indicated bluer tones.

Moisture content (%) was determined by oven-drying pre-weighed fiber samples at 105 °C until constant weight was achieved. The difference between the initial and final weight was used to calculate the moisture content. Mechanical properties were assessed using a Universal Testing Machine (UTM, Model NRI-TS500-20B). Each standardized fiber specimen was mounted in the testing clamps, and tensile testing was performed to determine maximum force (Max Force, N) and elongation at break. For each formulation, at least three specimens were tested to obtain mean values and standard deviations. All numerical data were analyzed using descriptive statistics (mean ± standard deviation), and one-way Analysis of Variance (ANOVA) was applied to evaluate significant differences among dyeing formulations for the measured parameters

(L*, a*, b*, moisture content, and tensile strength). A significance level of $p < 0.05$ was used to determine statistically meaningful differences.

Results

The researcher developed three experimental dye formulations to evaluate their effects on the coloration and fastness of *C. rotundus* fibers. The first formulation is presented below.

Table 1: Formulation 1 for dyeing *Cyperus rotundus* plant fibers with natural indigo

Ingredients	*Ratio*	*Steps / Timeframe*
Tap water (at ambient temperature)	10 L	1. Tap water, salt, and thiourea dioxide (reducing agent) were measured and placed into a plastic basin. The mixture was stirred until a clear solution was obtained without sediment. Fresh indigo paste was then added to the basin. 2. The indigo paste was stirred, kneaded, and crushed until fully dispersed into the solution. The mixture was left to rest for approximately 30 minutes until the dye liquor turned yellow, with blue foam appearing on the surface. 3. Dried *C. rotundus* plant fibers were submerged in the indigo dye bath for 48 hours. Every 24 hours, the fibers at the bottom were rotated to the top to ensure even dye penetration. 4. After 48 hours, the dyed fibers were removed, thoroughly rinsed with clean water, sun-dried until completely dry, and subsequently woven into experimental textile samples
Salt	120 g	
Thiourea dioxide	300 g	
Fresh indigo paste	1 kg	
Dried *C. rotundus* fibers	1 kg	

Resulting coloration is presented in figure 2.

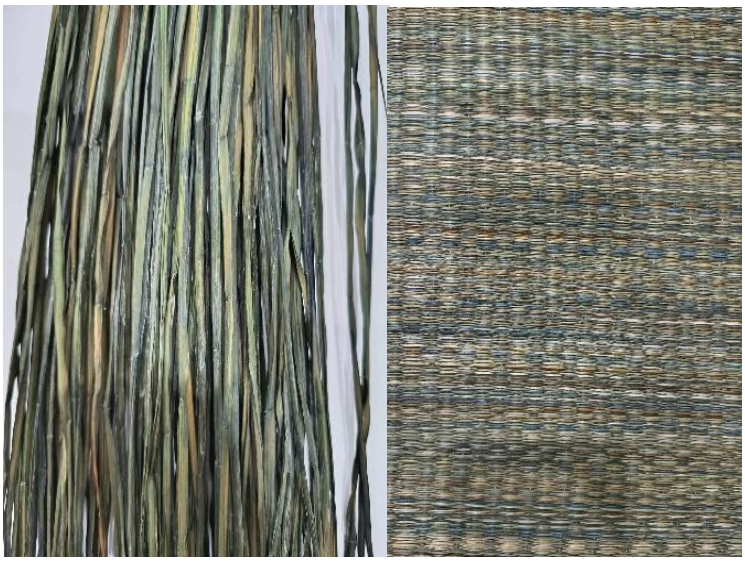

Figure 2: Coloration of *Cyperus rotundus* fibers after dyeing with natural indigo (Formulation 1) (*Source:* Chotinonphicha, 2025)

Indigo Dyeing Formulation 1

Based on the data in table 1, in which the primary ingredients were fresh indigo paste combined with *Cyperus rotundus* plant fibers, the resulting coloration of the fibers exhibited a gradient of hues ranging from bluish-green to dark green, transitioning to medium-green tones. In terms of dye uptake, the fibers demonstrated inconsistent absorption of color along their length, leading to uneven dye distribution. This irregularity in coloration indicates variability in the penetration of indigo molecules into the plant fibers when using this formulation.

Table 2: Formulation 2 for Dyeing Procedure (Formulation with Vinegar) *Cyperus rotundus* plant fibers with natural indigo

Ingredients	*Ratio*	*Steps / Timeframe*
Tap water (at ambient temperature)	10 L	1. Tap water, salt, vinegar, and thiourea dioxide (reducing agent) were measured and placed into a plastic basin. The mixture was stirred thoroughly until a clear solution without sediment was obtained. Fresh indigo paste was then added to the basin 2. The indigo paste was stirred, kneaded, and crushed until it fully dissolved and dispersed into the solution. The mixture was allowed to rest for approximately 30 minutes, during which the dye liquor gradually changed to yellow with the appearance of dark blue foam. 3. Dried *Cyperus rotundus* plant fibers were submerged in the indigo dye bath for 48 hours. To ensure even dye penetration, the fibers at the bottom of the basin were rotated to the top every 24 hours. 4. After 48 hours, the dyed fibers were removed, thoroughly rinsed with clean water, and sun-dried until completely dry. The indigo-dyed *C. rotundus* fibers were subsequently woven into experimental textile samples.
Salt	120 g	
vinegar	100 ML.	
Thiourea dioxide	300 g	
Fresh indigo paste	1 kg	
Dried *C. rotundus* fibers	1 kg	

Resulting coloration is presented in figure 3.

Dyeing Formulation 2

From table 2, the second indigo dyeing formulation, which consisted primarily of wet indigo paste, vinegar, and *Cyperus rotundus* (nutgrass) fibers, produced distinct variations in fiber coloration. The fibers exhibited shades ranging from green to light green, with gradations fading into yellow tones. However, the degree of dye fixation was found to be inconsistent along the entire length of the fibers. This uneven distribution of color suggests that while the addition of vinegar enhanced the interaction between the dye solution and plant fibers, the mordanting effect was insufficient to achieve uniform dye penetration and fixation across all fiber segments.\

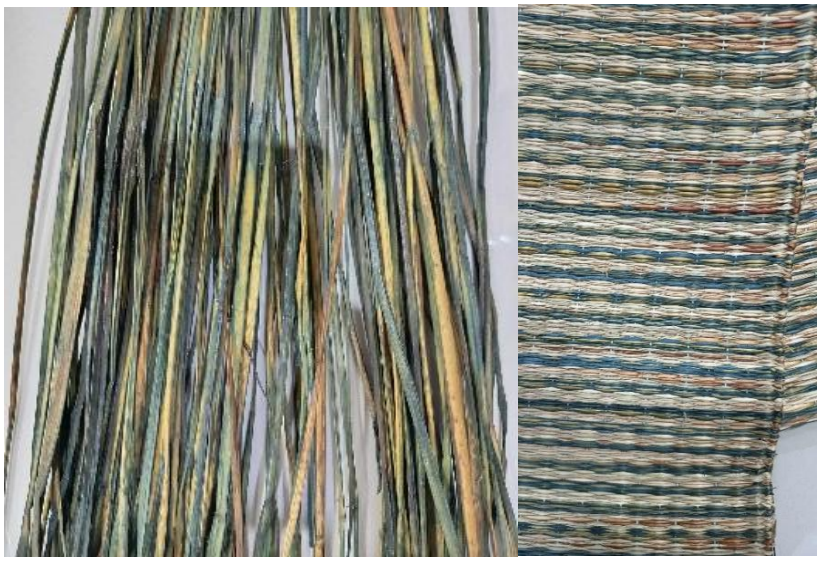

Figure 3: Coloration of *Cyperus rotundus* fibers after dyeing with natural indigo and Vinegar (Formulation 2) (*Source:* Chotinonphicha, 2025)

Table 3: Formulation 3 for Dyeing Procedure: Pre-treatment with Clay Solution and Vinegar Followed by Dyeing of *Cyperus rotundus* Plant Fibers with Natural Indigo

Ingredients	*Ratio*	*Steps / Timeframe*
Tap water (at ambient temperature)	10 L	Pre-treatment with Clay Solution 1. Tap water, Dan Kwian clay, salt, and vinegar were measured and placed into a plastic basin. The mixture was thoroughly stirred until homogeneous. Dried *Cyperus rotundus* plant fibers were then immersed in the clay solution for 24 hours. To ensure uniform treatment, the fibers at the bottom of the basin were rotated to the top every 12 hours. 2. After 24 hours, the fibers were removed, thoroughly rinsed with clean water to eliminate residual clay and other impurities, and sun-dried until completely dry. The pre-treated fibers were subsequently immersed in the prepared indigo dye bath for further processing.
Dan Kwian	1 kg	
Salt	120 g	
vinegar	100 ML.	
Fresh indigo paste	1 kg	
Thiourea dioxide	300 g	3. Tap water, salt, vinegar, and thiourea dioxide (reducing agent) were measured and placed into a plastic basin. The mixture was stirred until homogeneous and free from visible sediments. Fresh indigo paste was subsequently added. 4. The indigo paste was thoroughly kneaded, stirred, and crushed until completely dispersed in the solution. The dye liquor was left to rest for approximately 30 minutes, during which it turned yellow with the appearance of deep blue foam on the surface. 5. Dried *Cyperus rotundus* plant fibers were immersed in the dye bath for 48 hours. To ensure consistent coloration, the fibers were rotated every 24 hours, bringing the submerged fibers at the bottom to the top of the dye bath.

Ingredients	*Ratio*	*Steps / Timeframe*
		6. After 48 hours, the fibers were removed from the bath, washed thoroughly with clean water to remove excess dye and reducing agents, and sun-dried until completely dry. The indigo-dyed fibers were then woven into experimental textile samples for further analysis.

Resulting coloration is presented in figure 4.

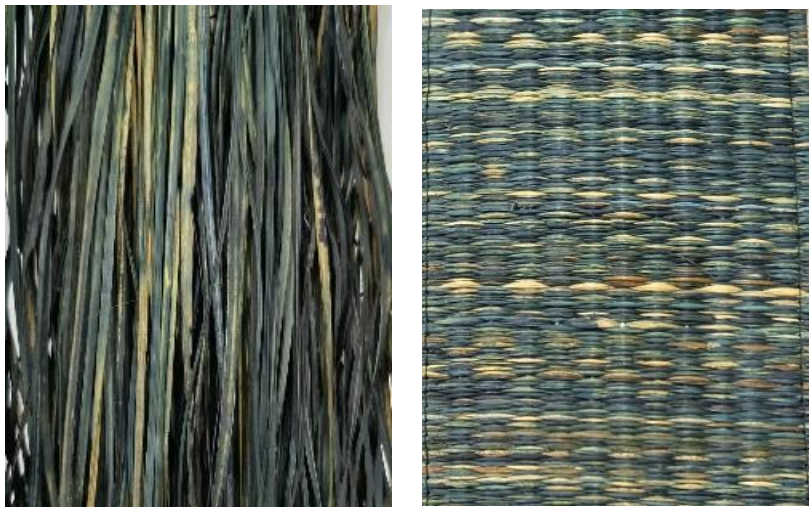

Figure 4: Coloration of *Cyperus rotundus* fibers Dyeing Procedure: Pre-treatment with Clay Solution and Vinegar Followed by Dyeing of *Cyperus rotundus* Plant Fibers with Natural Indigo (Formulation 3) (*Source:* Chotinonphicha, 2025)

Results of Indigo Dyeing Formulation 3

According to the table 3, the third dyeing formulation utilized Dan Kwian clay in combination with fresh indigo paste and *Cyperus rotundus* plant fibers. Following immersion in the indigo bath, the fibers exhibited a spectrum of colors, including dark blue, bluish-green, and deep green hues. However, the coloration was not uniformly distributed along the fiber strands, indicating uneven dye uptake.

Quantitative colorimetric analysis revealed that fibers dyed using Formulation 3 demonstrated the lowest mean L value (42.18 ± 0.85), indicating darker shades, with a* = –7.56 ± 0.42 and b* = –2.37 ± 0.51, reflecting a strong blue-green hue. Formulation 2 (indigo + vinegar) produced higher L* (54.62 ± 1.17) and b* values, giving lighter, yellowish-green tones, while Formulation 1 (indigo-only) yielded intermediate values. ANOVA results confirmed significant differences ($p < 0.05$) among formulations for all color parameters.

Colorimetric Analysis of Dyed Fibers

Color evaluation of indigo-dyed *C. rotundus* and *Cyperus mitis* fibers was conducted at the Fiber Testing Laboratory, Science Center, using standardized colorimetric

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techniques. The analysis focused on the interpretation of color coordinates in the CIELAB color space, with emphasis on the lightness (L*), red–green (a*), and yellow–blue (b*) axes. The results demonstrated distinct variations in color intensity between *C. rotundus* and *C. mitis* fibers when dyed with different indigo formulations. In particular, changes along the a* axis reflected shifts from green to red tones, while variations along the b* axis indicated transitions from blue toward yellow. These differences highlight the influence of mordant composition and clay pre-treatment on the overall hue and fastness of naturally dyed fibers, as shown in figure 5.

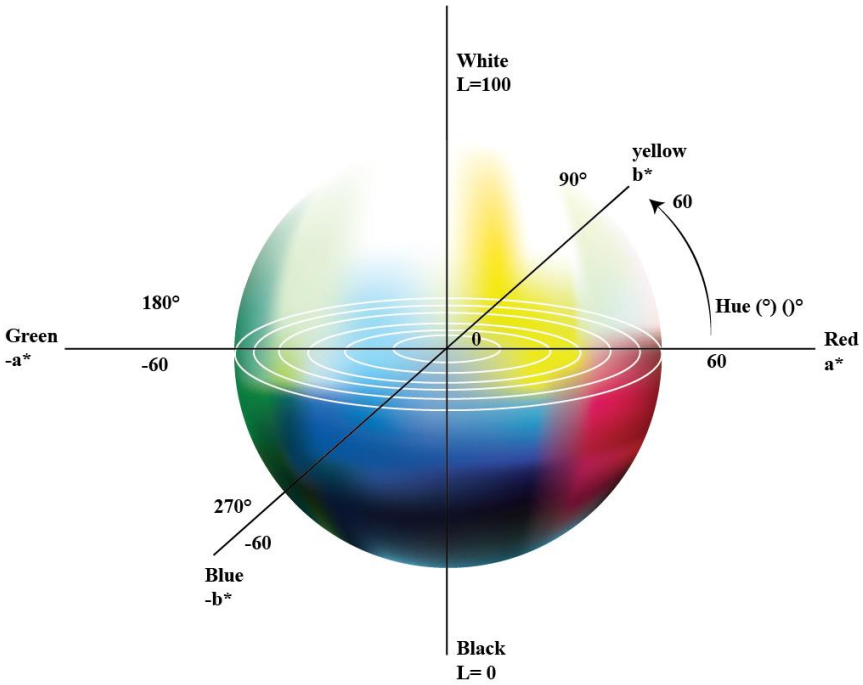

Figure 5: Illustration of the color measurement system indicating lightness (*Source:* Chotinonphicha, 2025)

The colorimetric evaluation of dyed fibers was conducted using the CIELAB color system, which consists of three variables: L*, a*, and b*. These parameters provide a standardized method for quantifying color characteristics as follows:

- *L*:* Represents lightness, ranging from 0 to 100, where 0 indicates black and 100 indicates white.
- *a*:* Describes the red–green axis, with negative values (−a*) representing green and positive values (+a*) representing red.
- *b*:* Describes the yellow–blue axis, with negative values (−b*) representing blue and positive values (+b*) representing yellow.

This system was applied to assess the color variations and intensity levels of *Cyperus rotundus* and *Cyperus mitis* fibers dyed with natural indigo under different formulations. *Interpretation of these values indicated that lower L* and more negative a* and b* coordinates corresponded to deeper, more saturated blue–green tones preferred in natural indigo craft applications. Among all formulations, Formulation 3 produced the most

desirable aesthetic outcome, combining visual richness with improved pigment fixation, as reflected by its lower L* and higher chromatic stability. Conversely, higher L* and positive b* values in Formulation 2 represented paler tones with weaker dye adherence. This system was applied to assess the color variations and intensity levels of *Cyperus rotundus* and *Cyperus mitis* fibers dyed with natural indigo under different formulations.

These results support previous findings that mineral-based mordants enhance color depth and fixation by facilitating ionic bonding between clay particles and fiber surfaces (Masae, Pitsuwan and Kongsong, 2024). This mechanism explains the enhanced hue stability observed in the Dan Kwian clay–treated fibers. Overall, the quantitative and interpretive analyses confirm that incorporating clay pre-treatment significantly improves both chromatic and practical quality of indigo-dyed Cyperus fibers, aligning aesthetic preference with measurable color performance.

The lightness values (L*) of dyed fibers were compared between *Cyperus mitis* and *C. rotundus* using three distinct indigo dyeing formulations:

1. *Formulation 1* – Natural indigo dye without additional mordants.
2. *Formulation 2* – Natural indigo dye combined with vinegar as an additional mordanting agent.
3. *Formulation 3* – Clay-based pre-treatment using Dan Kwian clay and vinegar, followed by immersion in natural indigo dye with vinegar.

The comparative analysis was conducted using a colorimeter under standardized laboratory conditions. The evaluation was designed to determine the influence of each formulation on the lightness parameter (L*) of the dyed fibers, which ranges from 0 (black) to 100 (white). The differences in lightness values provided insights into how mordanting agents and clay *pre*-treatment affected the overall visual perception, depth, and uniformity of color on plant-based fibers.

Table 4: Comparative analysis of lightness (L) and color coordinates (a*, b*) of *Cyperus mitis* and *Cyperus rotundus* fibers dyed with different natural indigo formulations*

Test	*L* (lightness)*	*a* (red–green)*	*B* (yellow–blue)*
Cyperus mitis plant fibers with natural indigo.	18.02	-3.37	3.51
Cyperus mitis plant fibers with natural indigo dyeing with natural indigo with vinegar as a mordant	37.98	-1.79	9.64
Cyperus rotundus plant fibers, natural indigo without mordants	27.47	-8.43	4.35
Cyperus rotundus plant fibers with natural indigo dyeing with vinegar as a mordant	35.48	-6.88	1.28
Pre-treatment with Dan Kwian clay and vinegar, followed by immersion in natural indigo.	15.94	-9.63	3.21

The comparative analysis of color lightness between *Cyperus mitis* and *C. rotundus* fibers was conducted under three different indigo dyeing conditions: (i) natural indigo without mordants, (ii) natural indigo with vinegar as a mordant, and (iii) pre-treatment with Dan Kwian clay and vinegar followed by immersion in natural indigo. For *C. rotundus* fibers dyed with natural indigo without vinegar, the color ranged from deep blue to dark green and bluish tones. Although the dye uptake was strong, the coloration was not evenly distributed along the fiber strands. The measured color coordinates were $a = -9.63$* (indicating a green shift) and $b = 3.21$* (indicating a slight shift toward yellow). For *C. rotundus* fibers subjected to clay pre-treatment before indigo dyeing, the resulting color shifted toward dark green to yellowish hues. Similar to the previous formulation, dye uptake was satisfactory but unevenly distributed along the fibers. The color coordinates were $a = -8.43$* and $b = 3.21$*. For *C. rotundus* fibers dyed with the vinegar-modified indigo bath, the resulting coloration ranged from light green to yellow. The fibers absorbed dye effectively, yet the color distribution remained inconsistent across fiber lengths. The corresponding values were $a = -6.88$* and $b = 1.28$*, suggesting a lighter greenish-yellow hue compared with the other formulations.

Overall, the analysis confirmed that the addition of mordants such as vinegar and clay pre-treatment influenced the chromatic characteristics of the fibers. Changes in a* and b* values reflected the progressive shift in hues, while variations in lightness levels highlighted the role of mordant composition in determining both the depth and uniformity of natural indigo coloration.

Moisture Content Analysis and Interpretation

The results of moisture content analysis obtained by the dry method are summarized in table 5. Two trials were conducted for each fiber group, and mean values were calculated for comparison. The findings revealed that untreated *C. rotundus* fibers exhibited the highest average moisture content (14.05%), whereas indigo-dyed *C. rotundus* fibers showed the lowest average moisture content (11.55%). This indicates that natural indigo dyeing reduced the ability of the fibers to retain moisture.

Table 5: Comparative analysis of moisture content (%) of Cyperus mitis and Cyperus rotundus fibers under different dyeing treatments using the dry method

Sample	*Moisture Content (%)*		
	Trial 1	*Trial 2*	*Mean*
Cyperus mitis plant fibers without natural indigo.	12.05	11.68	11.87
Cyperus rotundus plant fibers without natural indigo.	13.95	14.15	14.05
Cyperus rotundus plant fibers with natural indigo.	11.50	11.60	11.55
Pre-treatment with Dan Kwian clay and vinegar, followed by immersion in natural indigo.	11.86	11.70	11.78

The comparative results also suggested that indigo-dyed *C. rotundus* fibers demonstrated greater dryness compared with untreated *C. mitis* fibers (mean 11.87%)

and untreated *C. rotundus* fibers (mean 14.05%). This property suggests that indigo-dyed fibers possess enhanced resistance to moisture absorption and fungal growth relative to the other fiber types.

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Mechanical Property Evaluation

To further assess the suitability of indigo-dyed fibers for product development, the tensile strength and elasticity of fibers were tested. Fiber samples, including untreated *C. mitis* fibers, untreated *C. rotundus* fibers, and indigo-dyed *C. rotundus* fibers, were subjected to tensile testing using a Universal Testing Machine (UTM, Model NRI-TS500-20B). The instrument was used to determine maximum force (Max_Force, N) and elongation properties of the fibers. These measurements provided insights into the mechanical behavior of plant-based fibers and their potential for use as alternative materials in textile and craft applications.

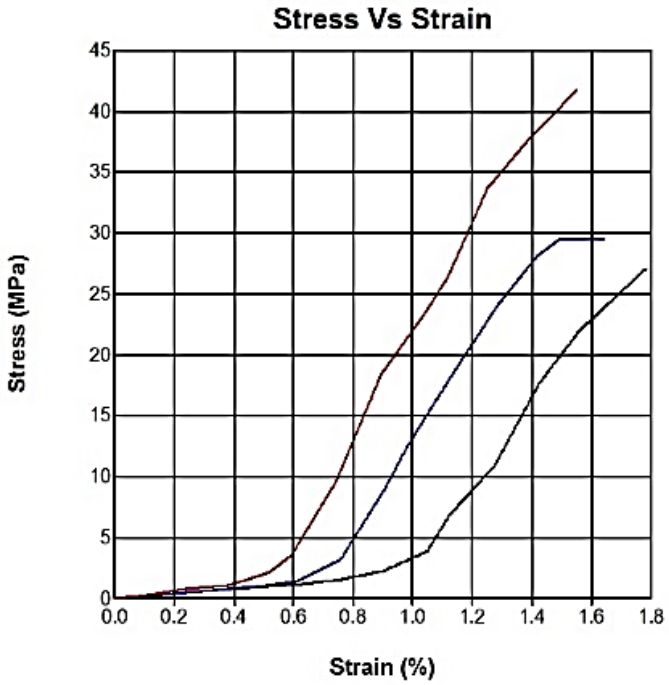

Figure 6: Graph of Tensile Strength and Elasticity of Cyperus *mitis* plant fibers without natural indigo

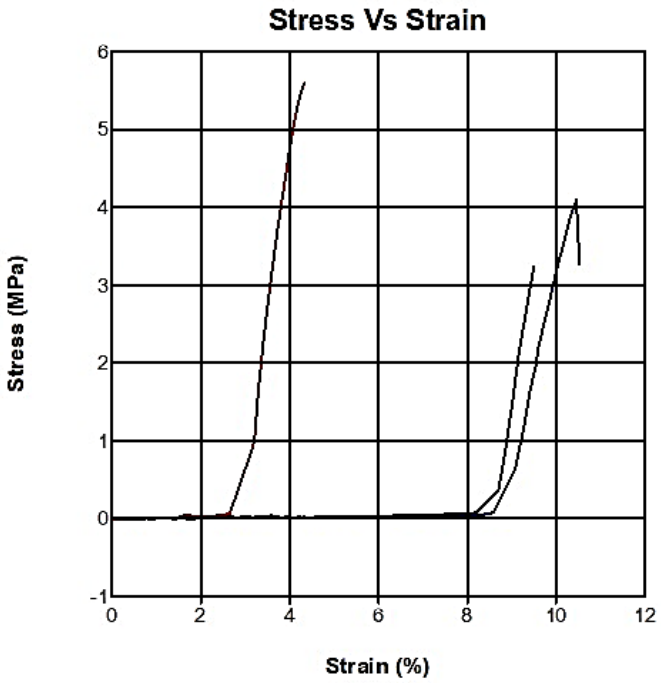

Figure 7: Graph of Tensile Strength and Elasticity of *Cyperus rotundus* plant fibers without natural indigo

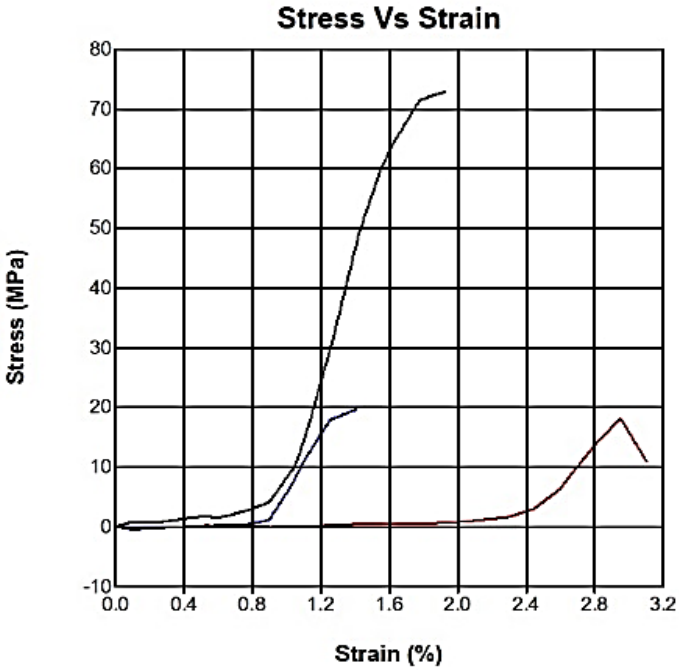

Figure 8: Graph of Tensile Strength and Elasticity *Cyperus rotundus* plant fibers with natural indigo

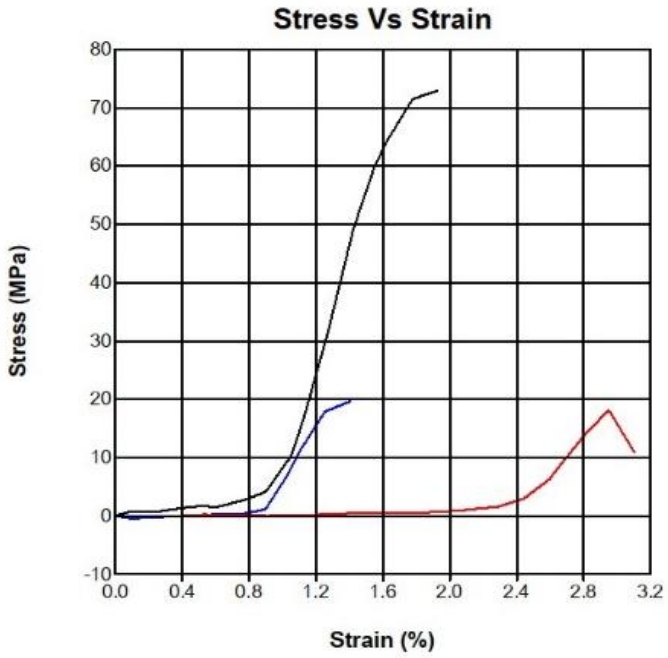

Figure 9: Graph of Tensile Strength and Elasticity pre-treatment with Dan Kwian clay and vinegar, followed by immersion in natural indigo

Mechanical Properties: Tensile Strength and Elasticity

The tensile strength analysis (Table 6) demonstrates significant differences among fiber groups. *Cyperus mitis* fibers without natural indigo recorded the highest tensile performance with an average force of 150.38 N, reflecting their superior mechanical integrity. Cyperus rotundus fibers without indigo also exhibited moderate strength (127.13 N), confirming their structural reliability in their untreated form. In contrast, Cyperus rotundus fibers dyed directly with natural indigo displayed the lowest tensile resistance, averaging 73.16 N. A slight improvement was observed when fibers underwent pre-treatment with Dan Kwian clay and vinegar before indigo immersion, yielding an average tensile strength of 75.76 N. Despite this enhancement, both dyed groups performed considerably below their undyed counterparts.

Overall, the results suggest that the indigo dyeing process negatively impacts the mechanical properties of Cyperus rotundus fibers, likely due to chemical penetration and microstructural changes that increase fiber brittleness. However, clay-vinegar pre-treatment offers a modest improvement in strength retention, suggesting potential for further optimization of mordanting techniques to balance dye adherence with fiber durability.

Table 6: Comparative tensile strength and elasticity (Maximum Force, N) of plant fiber samples

Test sample	*Point 1*	*Point 2*	*Point 3*	*Average*
Cyperus mitis plant fibers without natural indigo	132.94	144.75	173.46	150.38
Cyperus rotundus plant fibers without natural indigo	91.49	131.74	158.16	127.13
Cyperus rotundus plant fibers with natural indigo	112.15	44.54	62.78	73.16
Pre-treatment with Dan Kwian clay and vinegar, then natural indigo dye	98.52	57.38	71.38	75.76

Discussion

The findings of this study demonstrate the potential of *Cyperus rotundus* fibers as an alternative natural material for sustainable product development through the application of natural indigo dyeing techniques. When comparing the three dyeing formulations—(i) natural indigo only, (ii) natural indigo with vinegar as a mordant, and (iii) pre-treatment with Dan Kwian clay and vinegar followed by immersion in natural indigo—distinct differences were observed in terms of color intensity, uniformity, moisture content, and tensile strength of the dyed fibers. These outcomes are consistent with the broader literature on natural indigo dyeing of cellulosic fibers, where bath chemistry and mordant composition strongly influence shade depth and color stability (Shi *et al*., 2022)

Dye Uptake and Color Characteristics

The addition of vinegar as a mordant in Formulation 2 resulted in lighter color shades, predominantly green to yellowish tones. This outcome confirms that organic acids and dye bath pH significantly influence the chemical interactions between indigo molecules and cellulose-based substrates. Similar hue shifts and CIELAB trends—characterized by variations in L*, a*, and b* values—have been reported in studies of natural indigo dyeing applied to cotton and other cellulosic fibers, where pH-dependent reduction and oxidation processes affect final color expression (Hansepi and Laisram, 2022).

Beyond qualitative observations, the quantitative CIELAB data further reinforced these differences among dyeing formulations. In particular, lower L* values combined with more negative a* and b* coordinates observed in Formulation 3 indicate deeper and more saturated blue–green tones, which are generally regarded as desirable characteristics in traditional indigo craft aesthetics. This color behavior suggests enhanced pigment–fiber interactions facilitated by the mineral components of Dan Kwian clay, which may promote ionic or hydrogen bonding that stabilizes the indigo pigment layer within the fiber matrix.

The superior chromatic depth achieved through clay–vinegar pre-treatment is consistent with broader findings on the importance of mordanting strategy in natural dyeing systems. Nazir *et al.* (2022) demonstrated that premordanting cotton with plant-derived mordants extracted from agricultural wastes resulted in higher color strength compared

with post- or meta-mordanting, even under environmentally benign processing conditions. Similarly, the present results indicate that pre-treating *Cyperus rotundus* fibers with Dan Kwian clay and vinegar enhances dye–fiber interactions, leading to deeper blue–green hues without the use of metallic mordants. (Nazir *et al*., 2022).

Overall, these findings highlight the critical role of pre-treatment selection in determining chromatic quality and support natural-dyeing research that emphasizes the combined effects of pH, mineral content, and fiber chemistry on final coloration. The improved color depth observed in this study substantiates the value of integrating locally available clays into eco-dyeing practices, particularly within community-based craft production systems.

Tensile Strength and Mechanical Behavior

Mechanical testing indicated notable differences in tensile properties. *Cyperus mitis* fibers without dye exhibited the highest tensile strength (150.38 N), whereas *C. rotundus* fibers dyed with natural indigo recorded the lowest (73.16 N). Pre-treatment with clay and vinegar improved tensile strength slightly (75.76 N), though values remained significantly below those of untreated fibers. This suggests that indigo dyeing induces structural changes in fiber morphology, making them more brittle and less elastic. Comparable declines in tensile strength and elongation have been reported for natural-fibre composites and dyed cellulosic fibers when chemical or thermal treatments increase crystallinity and reduce fibrillar slippage (Faruk *et al*., 2012)

Despite reduced tensile performance, the mechanical properties of dyed fibers remained appropriate for weft applications in mat weaving, where compressive stability and dimensional rigidity are more important than high tensile strength. The findings thus indicate that these fibers are better suited for specific product types rather than general textile applications requiring greater flexibility or load-bearing capacity

Implications for Sustainable Material Development

Although indigo-dyed *Cyperus rotundus* fibers exhibited reduced tensile strength, their eco-friendly characteristics, such as biodegradability, resistance to moisture, and compatibility with traditional weaving, make them viable alternatives for community-based product innovation. Specifically, they are suitable for woven applications such as mats or fabric panels, where tensile flexibility is less critical compared to durability and environmental performance. Moreover, the study provides evidence that natural dyeing not only valorizes an invasive weed but also transforms it into a marketable material aligned with the principles of the bio-circular-green (BCG) economy.

This research demonstrates how integrating local resources, such as Dan Kwian clay and naturally available Cyperus fibers, strengthens community resilience by reducing dependence on synthetic dyes and imported materials. The approach also contributes to carbon reduction, supports zero-waste principles, and expands the scope of eco-lifestyle products that communities can produce for domestic and international markets.

Limitations and Future Research

Despite promising results, such as the prototype products developed from indigo-dyed *Cyperus rotundus* fibers (Figure 10), this study highlights several limitations. First, the uneven dye distribution across fibers requires optimization of mordanting and soaking times to achieve consistent coloration. Second, the reduction in tensile strength suggests the need for blending *Cyperus rotundus* fibers with other natural fibers (e.g., cotton, hemp, or banana fibers) to enhance mechanical performance while retaining eco-friendly properties. Finally, future studies should assess color fastness against washing, sunlight, and abrasion in accordance with ISO standards to establish industrial applicability.

Further work should also investigate microstructural changes in dyed fibers using microscopy or spectroscopy techniques to better understand the interactions between indigo pigments, clay minerals, and cellulose fibrils. In addition, scaling up the dyeing process using Technology Readiness Level (TRL) assessment could determine feasibility for community-level production, while Social Readiness Level (SRL) evaluation would help identify adoption potential among local artisans.

Figure 10: Prototype Product Developed from Indigo-Dyed *Cyperus rotundus* Fibers (*Source:* Chotinonphicha, 2025)

Conclusion

The comparative evaluation of the three indigo-dyeing formulations applied to *Cyperus rotundus* fibers showed that pre-treatment with Dan Kwian clay and vinegar produced the deepest and most saturated indigo shades, although the color distribution was not fully uniform. Formulations using indigo alone or indigo with vinegar resulted in lighter hues and less chromatic depth. The dyeing process also reduced moisture content and altered mechanical integrity, making the fibers drier and less flexible than their untreated counterparts. These changes suggest that dyed *C. rotundus* fibers are better suited for woven applications where moderate flexibility is sufficient and environmental performance is prioritized.

Overall, the study highlights the potential of transforming an invasive plant species into a sustainable raw material aligned with bio-circular-green (BCG) principles. By

integrating traditional indigo dyeing with material testing, the findings demonstrate that *C. rotundus* fibers can support community product innovation and provide environmentally conscious alternatives to synthetic fibers. Future work should focus on improving dye uniformity, optimizing mordant conditions, exploring fiber blending to enhance strength, and conducting standardized fastness testing to expand opportunities for practical and industrial applications.

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References

Aphirakthanakorn, P. (2017). Eco Design Thai Thai. Available online at: https://buffet.ookbee.com/book/433d8239-5b5b-4043-9de5-eea9ba102495 [accessed on 1 December 2025]. (In Thai).

Bangkok Bank (2022). Green voice: Consumer behavior trends towards eco-friendly products. Bangkok Bank Research Division. Available online at: https://www.bangkokbank.com/-/media/files/about-us/sd/the-great-green-transition/summary-the-great-green-transition.pdf [accessed on 12 July 2025] (In Thai).

Bangkokbiznews (2024). Thailand's lifestyle and fashion exports outlook 2024. Bangkokbiznews. Available online at: https://www.bangkokbiznews.com [accessed 21 September 2025] (In Thai).

Chotinonphicha, A. (2025). The Transformation of Agricultural Weeds such as Sedge for Design and Development into Eco Products. *Journal of Asia Arts and Design,* 6(2): 106-122. Available online at: https://so01.tci-thaijo.org/index.php/jaad/article/view/284308 [accessed on 1 December 2025]. (In Thai).

Chollakup, R., Rungruangkitkrai, N., Apipatpapha, T., Witayakran, S., Nithithongsakol, N. and Mongkholrattanasit, R. (2023). A Study on the Woven Construction of Fabric Dyed with Natural Indigo Dye and Finishing for Applying to Product Design for Home Textile Products. *AUTEX Research Journal*. 23(1): 116-125. DOI: https://doi.org/10.2478/aut-2021-0050.

Department of Agriculture (2022). Cyperus mitis management technologies. Bureau of Plant Protection Research and Development, Department of Agriculture. Ministry

of Agriculture and Cooperatives, Bangkok. Available online at: https://www.doa.go.th/plprotect/wp-content/uploads/2022/10/2565-%E0%B9%81%E0%B8%AB%E0%B9%89%E0%B8%A7%E0%B8%AB%E0%B8%A1%E0%B8%B9-watermark_compressed.pdf [accessed on 14 August 2025] (In Thai).

Department of Land Development (2021). Soil and clay utilization for eco-dyeing applications. Ministry of Agriculture and Cooperatives, Bangkok. Available online at: http://www1.ldd.go.th/WEB_PSD/pdf/expert%20work/ex18-3/3-2.pdf [accessed on 12 July 2025] (In Thai).

Department of Sericulture (2023). *Research and development on natural dyes in Thai silk*. Bureau of Sericulture Research and Development, Ministry of Agriculture and Cooperatives, Bangkok. Available online at: https://qsds.go.th/newosrd/%E0%B8%A7%E0%B8%B1%E0%B8%AA%E0%B8%94%E0%B8%B8%E0%B8%A2%E0%B9%89%E0%B8%AD%E0%B8%A1%E0%B8%AA%E0%B8%B5/ [accessed on 5 July 2025]. (In Thai).

Dhunkhunthod, J., Clongsamsib, S., Vinai,T. and Wisansakkul, S. (2024). Effects of using dyes from coffee grounds for dyeing bamboo strips in handicrafts. *Thai of Journal of Home Economics Technology and Innovation*. 3(1). DOI: https://doi.org/10.60101/jhet.2024.792. (In Thai).

Faruk, O., Bledzki, A.K., Fink, H.P. and Sain, M., (2012). Biocomposites reinforced with natural fibers: 2000–2010. *Progress in Polymer Science*, 37(11): 1552-1596. DOI: https://doi.org/10.1016/j.progpolymsci.2012.04.003.

Hansepi, L. and Laisram, R. (2022). Karbi Women and Environmental Conservation. *Grassroots Journal of Natural Resources*, 5(3): 1-17. DOI: https://doi.org/10.33002/nr2581.6853.050301.

Hohol, T. and Nedilska, U. (2021). The Sustainable Use of Natural Resources in Rural Areas of Ukraine: The Governance Challenge. *Grassroots Journal of Natural Resources*, 4(4): 76-84. DOI: https://doi.org/10.33002/nr2581.6853.040406.

Kaenchan, S. and Khamphiraphanphan, P. (2014). Dyeing silk with coffee grounds using pomegranate peel extract as a fixative. *Thai Report Reseach of Rajamangala University of Technology Bangkok*. Available online at: https://dspace.rmutk.ac.th/jspui/bitstream/123456789/105/1/1-123-1-PB.pdf [accessed on 12 July 2025] (In Thai).

Masae, M., Pitsuwan, P. and Kongsong, P. (2021). UV protection of silk dyed with cassava leaves. *Thai Journal of Engineering and Innovation:* 14(3): 144-148. Available online at: https://ph02.tci-thaijo.org/index.php/eng_ubu/article/view/245132/166220 [accessed on 21 November 2025]. (In Thai).

Mongkholrattanasit, R., Klaichoi, C., Rungruangkitkrai, N., Vuthiganond, N. and Nakpathom, M. (2022). Eco-Printing on Cotton Fabric with Natural Indigo Dye Using Wild Taro Corms as a New Thickening Agent. *Journal of Natural Fibers*, 19(13). DOI: https://doi.org/10.1080/15440478. 2021. 1875381.

National Innovation Agency (2019). Thailand's innovation performance in the Global Innovation Index 2019. Ministry of Higher Education, Science, Research and Innovation, Bangkok. Available online at: https://nia.or.th/pdf/books/Innovation%20for%20the%20Future.pdf [accessed on 4 July 2025] (In Thai).

Nazir, F., Siddique, A., Nazir, A., Javed, S., Hussain, T. and Abid, S. (2022). Eco-friendly dyeing of cotton using waste-derived natural dyes and mordants. *Coloration Technology*. 138(6): 684-692. DOI: https://doi.org/10.1111/cote.12629.

Olas, B., Białecki, J., Urbańska, K. and Bryś, M. (2021). The Effects of Natural and Synthetic Blue Dyes on Human Health: A Review of Current Knowledge and Therapeutic Perspectives. *Advances in Nutrition,* 12(6): 2301-2311. DOI: https://doi.org/10.1093/advances/nmab081.

Pizzicato, B., Pacifico, S., Cayuela, D., Mijas, G. and Moliner, M.R. (2023). Advancements in Sustainable Natural Dyes for Textile Applications: A Review. *Molecules*, 28(16): 5954. DOI: https://doi.org/10.3390/molecules28165954.

Reemsri, J. and Khieokaew, C. (2019). Identity Communication Straregy of Indigo Dyed in Sakon Nakhon**.** *Thai Journal of MCU Social Science Review*, 8(4): 178-190, Available online at: https://so03.tci-thaijo.org/index.php/jssr/article/view/224731 [accessed on 23 October 2025] (in Thai).

Saxena, S. and Raja, A.S.M. (2014). *Natural Dyes: Sources, Chemistry, Application and Sustainability Issues*. *Water Resources Development and Management.* 37–80. DOI: https://doi.org/10.1007/978-981-287-065-0_2.

Shi, Y., Libin, Z., Lu, W., Shan, L., Zuchuan, Q., Xiaoyong, D. and Yuhua, W. (2021). Quality blues: traditional knowledge used for natural indigo identification in southern China, *Journal of Ethnobiology and Ethnomedicine,* 17(25). DOI: https://doi.org/10.1186/s13002-021-00454-z.

Shrestha, S., Shrestha, J. and Shah, K.K. (2022). Non-Timber Forest Products and their Role in the Livelihoods of People of Nepal: A Critical Review. *Grassroots Journal of Natural Resou*rces. 3(2): 42-56. DOI: https://doi.org/10.33002/nr2581.6853.03024.

Tharinphirom, P. (2020). Beautiful World Marketing Voice of Green: For the World, For Us. Research report on College of Management, Mahidol University. Available online at: https://www.sdperspectives.com/next-gen/voice-of-green-cmmu/ [accessed on 4 July 2025]. (in Thai)

Toponar, O., Shpatakova, O., Kopchak, Y., Klievtsievych, N. and Miniailenko, I. (2022). Integrating the Circular Economy into Business Processes to Reduce Waste and Increase Environmental Sustainability. *Grassroots Journal of Natural Resources*, 7(2): 140-159. DOI: https://doi.org/10.33002/nr2581.6853.070207.

Torabizadeh, M., Yusof, N.M., aram, A.M. and Shaharoun, A.M. (2020). Identifying sustainable warehouse management system indicators and proposing new weighting method. *Journal of Cleaner Production*, 248: 119-190. DOI: https://doi.org/10.1016/j.jclepro.2019.119190.

Weisburger, J.H. (2002). Comments on the history and importance of aromatic amines in public health. *Mutation Research/Genetic Toxicology and Environmental Mutagenesis*, 506–507: 9–20. DOI: https://doi.org/10.1016/S0027-5107(02)00147-1.

WIPO (2019). *Global Innovation Index 2019*. Geneva: World Intellectual Property Organization.

Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*
Conceived and designed the research or analysis	Yes	No
Collected the data	Yes	No
Contributed to data analysis & interpretation	Yes	Yes
Wrote the article/paper	Yes	Yes
Critical revision of the article/paper	Yes	No
Editing of the article/paper	Yes	No
Supervision	Yes	No
Project Administration	Yes	No
Funding Acquisition	Yes	No
Overall Contribution Proportion (%)	80	20

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Research involving human bodies or organs or tissues (Helsinki Declaration)
The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

Research involving animals (ARRIVE Checklist)
The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

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The author(s) has/have NOT complied with PRISMA standards to an extent.

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